The maps would give additional knowledge of the free-air winds. From the examples given in this paper it is obvious that many cases occur when the free-air conditions can not be accurately judged from sea-level data. These often occur at times of stormy weather when pilot-balloon observations are not available. Such times are likewise trying to the aviator, and it is then that he wants the most reliable advice.

It is believed that these maps will eventually have significance for general forecasting because of the close relation between free-air conditions and certain phases of surface weather, precipitation, cloudiness, and temperature. If these maps are found useful in the eastern United States and those tentative plans which have been suggested above for attacking the pleateau are found fruitful, there is the encouraging possibility that we may realize an ambition to blanket our country from coast to coast with a weather map of three dimensions. This may not be a universal panacea for all forecasting ills, but it will at least afford a glimpse of the physical processes at work, and lift us from the annoying disappointments of empiricism a little nearer to that ultimate goal toward which all students of weather forecasting are striving.

J. BJERKNES AND H. SOLBERG ON THE LIFE CYCLE OF CYCLONES AND THE POLAR FRONT THEORY OF ATMOSPHERIC CIRCULATION.[1]

By ALFRED J. HENRY.

[Weather Bureau, Washington, D. C., November 3, 1922.]

These two young Norwegian meteorologists have our best thanks for the clear presentation of their views on that perpetually interesting question of the origin and maintenance of cyclones and anticyclones. Readers of the REVIEW have had some intimation of the research work in forecasting that is being conducted at the Bergen Geophysical Institute from Miss Beck's paper in the August issue.[2] That article will serve as a prelude to the more formal presentation of the subject in the paper under review.

The elder Bjerknes, from a study of weather charts on which lines of flow were depicted and from other considerations, was led to a theory of the formation of cyclones and anticyclones, the germs of which, according to his own statement, are to be found in the writings of Dove and Helmholz. The latter in a paper on Atmospheric Motions[3] has shown that there is always a tendency toward the formation of a surface of discontinuity between air strata of different density which lie contiguous one above the other, and that at the bounding surfaces of such strata the conditions are ripe for the formation of atmospheric waves as soon as a lighter stratum lies above a denser one.

Professor Bjerknes has developed these ideas and applied them to the explanation of the origin and maintenance of cyclones and anticyclones. The air strata of different density most frequently met in nature are the two great currents, one flowing toward the Pole, the other toward the Equator. In a sense these are the counter currents of Bigelow and the opposing currents of Dove. How these currents act and react to form cyclones and anticyclones is perhaps best visualized from a drawing which the authors present under the title "Idealized cyclone." This diagram appeared in the August REVIEW, on page 404. They describe the principal features of the cyclone as consisting of two essentially different air masses, the one of cold, the other of warm origin. The two air masses are separated by a fairly distinct boundary surface which runs through the cyclone and which the authors believe may continue more or less distinctly through the greater part of the troposphere, being everywhere inclined toward the cold side at a small angle with the horizontal, say 1° or even 0.1°.

In the Northern Hemisphere the warm air is conveyed by a southwesterly or a westerly current on the southern side of the depression.[4]

At the front of this current the warm air ascends the wedge of colder air and gives rise to precipitation (warm front rain).[5]

The warm current is simultaneously attacked on its flank by cold air masses from the rear of the cyclone. Thereby part of the warm air is lifted and precipitation is formed (cold front rain).[6]

THE LIFE CYCLE OF CYCLONES.

The authors say that the more recent investigations have shown that the type of cyclone above described represents a certain stage of development in the life of a cyclone. The successive changes in form and structure are schematically shown in Figure 1, in which type *c* or *d* corresponds to the "ideal" cyclone mentioned above.

In the earlier stages the same cyclone has the structure shown in *a* and *b* and it will successively pass through the forms *e, f, g,* and *h* of Figure 1. As may be seen by that figure, the initial stage of formation is pictured in *a* wherein two oppositely directed currents a cold easterly (from the east) adjacent to and on the same level with a warm westerly (from the west) is separated by a nearly straight boundary.

At the place where the new cyclone is to be formed this originally straight boundary bulges out toward the cold side as in *b*, and the center of the cyclone will be found at the top of the projecting tongue of warm air. The tongue of warm air is identical with the warm sector of the cyclone, and the ascending air from this warm tongue forms the "warm front" rain and the "cold front" rain shown in *c* and *d*, respectively. This newly formed cyclone follows the current of warm air eastward and is propagated as a wave on the boundary surface between warm and cold air.

During the eastward motion, the amplitude of the warm wave increases (in a horizontal N-S direction as in

[1] *Geofisiske Publikationer*, Vol. III, No. 1: Kristiania, 1922.

[2] Pages 393-400.

[3] The mechanics of the earth's atmosphere. A collection of translations by C. Abbe, *Smithsonian Collections No. 843.*

[4] For the eastern part of the United States I should say that this specification should be modified to read the warm current is conveyed by a southwesterly to a southeasterly current on the southern or eastern side of the depression.—EDITOR.

[5] This is, of course, a very generalized statement to which there are many exceptions, so far as precipitation is concerned. In the case of a shift of the wind from offshore to onshore, when the land surface is quite cold precipitation occurs regardless of the position of the cyclone center, particularly along the Middle Atlantic coast.—EDITOR.

[6] In the United States cold front precipitation is not strongly marked in winter except as snow flurries in mountain districts and on the lee shores of the Great Lakes; in summer, however, the precipitation of a cyclone may be confined to cold front rain, which in many cases is clearly associated with the "wind shift" line in the rear.—EDITOR.

Figure 1*c*). Cold air curves around the northern end of the warm air and arrives in the rear of the cyclone as a northwesterly wind. This type corresponds to the previously described "ideal" cyclone. Simultaneously with the further increase in amplitude (Fig. 1*d*) the tongue of warm air narrows laterally, especially in the southern part of the cyclone. Finally as in Figure 1*e* cold air from the rear joins the cold air in front and thus cuts off the supply of warm air. In this phase the cyclone is said to be "secluded." The remaining part of the warm sector, near the center, also soon disappears so that the cyclone on the ground consists of cold air only. (Fig. 1.) For this type the authors have chosen the term "occluded" cyclone. At the place where the warm sector disappeared, a boundary line persists for some time between the cold air from the rear and the front of the cyclone, respectively. Finally, this boundary also disappears, Figure 1*g*, and the cyclone becomes a nearly symmetrical vortex of cold air. The large zones of continuous rain have then disappeared and precipitation occurs only as intermittent showers. These conditions then persist until the cyclone is wasted away.

During the first phase of the development of the cyclone —from its origin to the moment of occlusion—the warm air is lifted by the two wedges of cold air as they gradually approach each other. This process transforms part of the potential energy of the initial system into kinetic energy and from this fact the authors predicate the following rule: *All cyclones which are not yet occluded have increasing kinetic energy.* This is exemplified on the weather maps by an increase of wind force and usually a deepening of the depression. When a cyclone is found to be of the type shown by Figure 1 *a*, *b*, *c*, or *d* it may be forecast with great confidence that it will deepen.

After the two wedges of cold air have met on the ground the still existing upper warm sector will be further lifted by the cold air until it is cooled adiabatically to the temperature of air at the same level into which it ascends. As long as this stage has not been reached, kinetic energy will be gained by the process. Later, when the cyclone has become a homogeneous air vortex, it has no store of potential energy, and the existing motion can only be maintained by the inertia of the moving air-masses.

From the moment of occlusion—that is, when the cold air on the ground in the front and rear of the cyclone join—portions of the cold air must also begin to rise. This ascending motion is, however, not directly due to gravity. The adiabatic cooling will soon make the ascending column of cold air colder than its surroundings on the same level, so that the force of gravity will counteract the ascending motion of the cyclone. The kinetic energy of the cyclone from that movement is used to pump the cold air upward against gravity, a process by which the system loses kinetic energy. Thus in the interval of time just after occlusion kinetic energy is gained in the higher layers and lost in the lower. The first process, however, will stop just as soon as the upper warm sector reaches the layers having its own potential temperature, and the effect of the second process will finally alone determine the transformation of energy in the cyclone. Friction of air-masses favors the second process, so that the influences which cause kinetic energy to be transformed will soon preponderate after the occlusion takes place.

Therefore, the following precept: *After the occlusion the cyclone soon begins to fill up.*

The authors specifically state that their considerations of the problem have been upon the supposition that the warm and the cold air masses are separated by sharply defined boundaries or real surfaces of discontinuity—an ideal condition that is never perfectly fulfilled—and, further, that no thermal boundary surface forms between the two wedges of cold air meeting each other at the occlusion of the cyclone. They are of opinion that so far as the mechanism of the cyclone is concerned it makes no

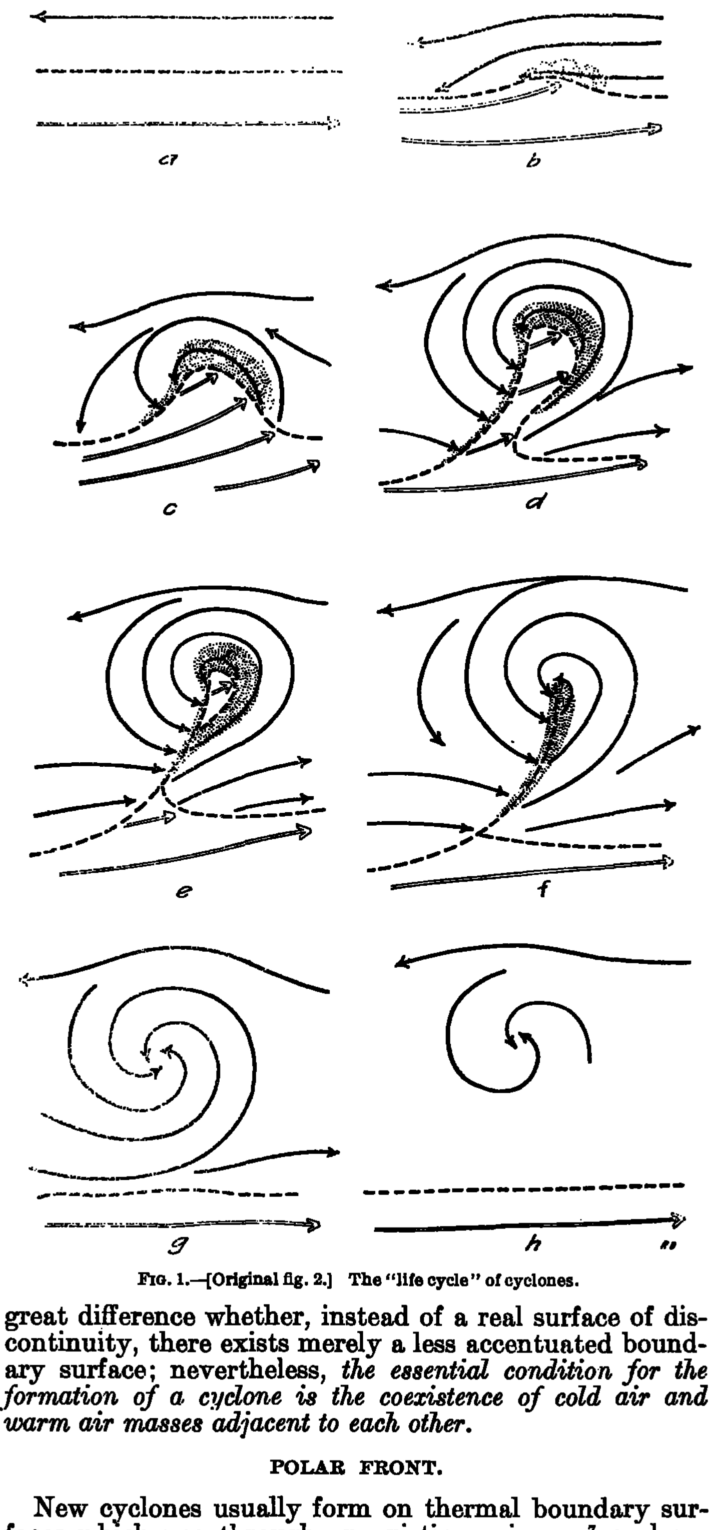

FIG. 1.—[Original fig. 2.] The "life cycle" of cyclones.

great difference whether, instead of a real surface of discontinuity, there exists merely a less accentuated boundary surface; nevertheless, *the essential condition for the formation of a cyclone is the coexistence of cold air and warm air masses adjacent to each other.*

POLAR FRONT.

New cyclones usually form on thermal boundary surfaces which run through an existing primary[7] cyclone.

[7] The reviewer has taken the liberty of substituting "primary" for "mother" when the latter appears in the text.

The formation may take place according to either of the two schemes graphically presented in Figures 2 and 3. The most common type is that shown in Figure 3. In that illustration the cold front boundary surface, the dashed line, has a northward inflection some distance in the rear of the primary cyclone; a situation similar to that illustrated in Figure 1*b*. With this initial impulse, however brought about, it is easy to see that the results figured in the lower part of Figure 3 will follow.

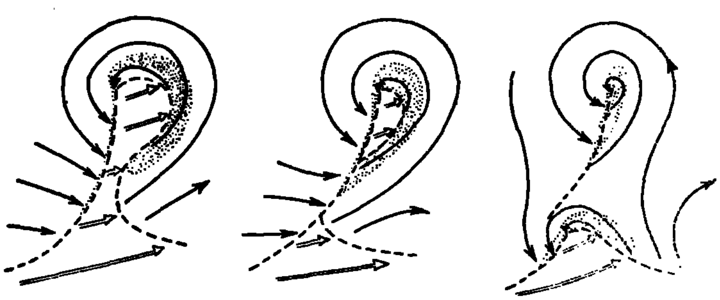

FIG. 2.—[Original fig. 6.] Formation of a secondary cyclone simultaneously with the seclusion of the primary cyclone.

Figure 4 illustrates the development of a series of cyclones along the polar front. The boundary surface connecting such a series of cyclones in the Temperate Zone will separate the cold air of polar origin from the warm air supplied by the subtropical HIGHS. The boundary surface thus marks the southern limit of the polar [8] air masses, a property which suggested the term "polar front surface" and accordingly for its intersection with the ground "polar front." The polar front is conceived in general as a wavy line in continual motion through all latitudes of the Temperate Zone, bordering large projecting masses of polar and tropical air.

The projections of tropical air form the warm sectors of newly formed traveling cyclones, and the intermediate projection of polar air form the moving wedges of high pressure between successive cyclones.

Suggestions as to locating the polar front.—The trajectories of air may be used to find an indistinct boundary line which was distinct on previous maps. When exact measurements of air motion are not available, the gradient wind may be used as representative of the upper wind, which determines the displacement of air masses and their mutual boundary surfaces; it should be borne in mind that a cold front must move at least as fast as the horizontal flow of cold air behind it, provided it does not ascend. On the other hand, a warm front will usually move somewhat slower than the horizontal flow of air behind as the latter ascends the wedge of cold air in front of it.

The absolute humidity of the air may be used to identify air masses and boundaries between different air masses in cases when insolation or radiation have effaced the thermal discontinuity. At stations on the sea coast the differences between the air temperature over the sea and over the land, respectively, may be used to determine the origin of the air.

Temperature in the free air from kites or aeroplanes are also useful in the analysis of the polar front.

[8] The reviewer interprets the expression "polar" air to mean any mass of air which for the time being is colder than its surroundings, regardless of its apparent origin. On weather charts which do not include the higher latitudes it is not always possible to determine the origin of the air streams portrayed on the map.

THE CYCLONE FAMILIES.

In a series of cyclones formed on one and the same polar front, each cyclone usually follows a track lying south of that of the preceding cyclone. After a certain number of such cyclones the polar front reaches the region of the subtropical HIGHS, whence a steady transport of air takes place through the trade winds toward the Equator. In some conspicuous cases the arrival of polar air may be observed as a sudden but slight decrease of the temperature of the trade wind, but usually the polar air soon amalgamates with the adjacent tropical air. The polar air thus entering the trades leaves the cyclonic circulation of the Temperate Zone for a considerable length of time and will be transferred into real tropical air during its stay in equatorial regions. The authors next lay down the following precept: *When the polar air from the rear of one cyclone enters the trade winds the next cyclone will usually appear on a more northern track* and follow a new polar front, which is not directly connected with the previous one.

On this new polar front the same phenomenon will be reproduced as on the old polar front. The cyclones will follow, step by step, more southern tracks until the polar air again reaches the Tropics and the same cycle of events is repeated.

This periodicity enables us to divide cyclones into groups which have been called cyclone families.[9]

Each family begins with the first cyclone traveling along a track north of that of the preceding cyclone and ends with the cyclone traveling so far south that it brings the polar air down into the trade-wind system. All cyclones of one family are thus formed on one and the same polar front. Moreover, each new family is formed on another polar front not connected with either the polar front of the foregoing or of the following cyclone families. When such a cyclone family passes usually four individual cyclones are observed from a fixed place, centrally within the cyclone belt. This number may, however, vary considerably from one family to another.

The single members of a cyclone family are usually of different ages. In Europe the first and second cyclones of any family, which for convenience may be called the A and B cyclones are mostly of the vanishing type when they arrive from the Atlantic. The later members, the C and D cyclones are, however, mostly of less age and show increasing intensity during their passage over Europe.

From these facts the conclusion is reached that the A and B cyclones are formed relatively far west of Europe and have traveled for several days before arriving at the western coast of that Continent, whereas the C and D cyclones are formed nearer to Europe. Accordingly we may expect the A cyclone to vanish within the region embraced by the Norwegian weather map, while the B cyclone will pass farther to the eastward and the C and D cyclones still farther before they disappear.

When the A cyclone vanishes the B cyclone becomes the foremost member of the family, when the B cyclone vanishes the C cyclone becomes the foremost member and so on.

Although the single cyclone usually persists only about a week, the cyclone family may theoretically live indefinitely, since it is being renewed by the creation of new cyclones behind the vanishing ones.

[9] Cf. Mo. WEATHER REV. 50: 16-20.

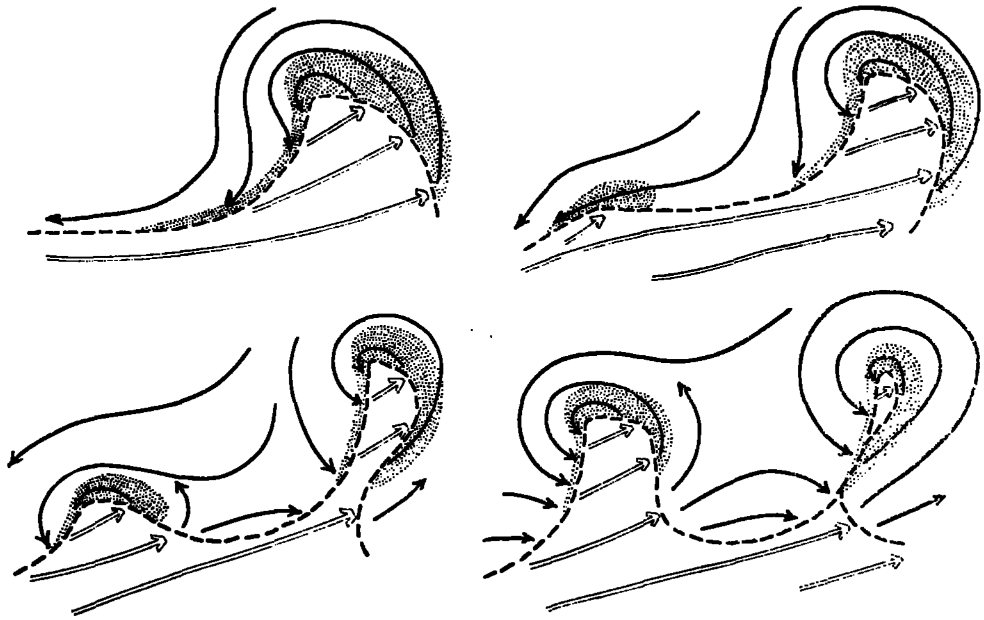

FIG. 3.—[Original fig. 8.] Formation of a secondary cyclone as a wave on the cold front of the primary cyclone.

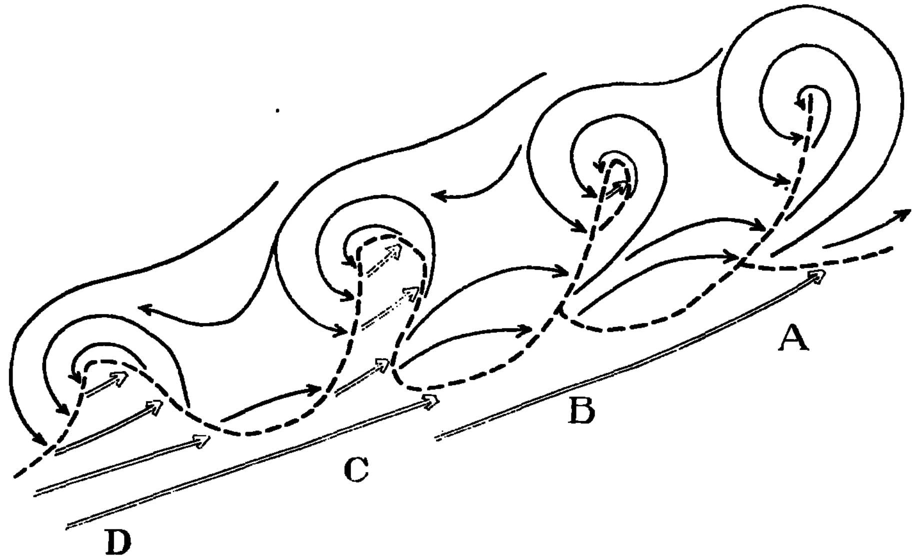

FIG. 4.—[Original fig. 9.] The polar front through a series of cyclones.

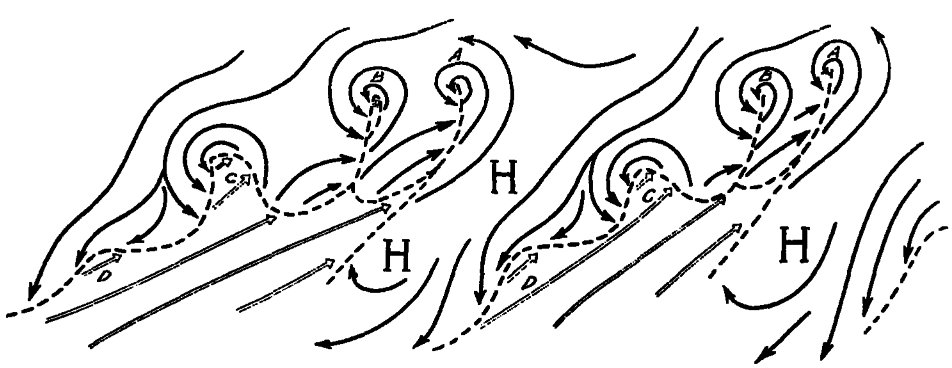

FIG. 5.—[Original fig. 10.] Cyclone families.

THE POLAR-FRONT THEORY OF THE GENERAL ATMOSPHERIC CIRCULATION.[10]

The final part of the paper bears the above title with a separate paragraph upon periods in the meteorological elements due to cyclone families and moving anticyclones.

The theory is given in the author's own words as follows:

The source of energy for the general circulation of the atmosphere lies in the contrast of temperature between the polar and the equatorial regions. The system of motion which is comprised under the name "General circulation" tends to smoothe the contrast by bringing polar air to tropical regions, and vice versa. The simplest form of this system, a trade wind along the ground from polar to equatorial regions and a returning antitrade in the height, is on higher latitudes impossible on account of the effect of the earth's rotation. The trades would after some travel southward obtain a strong westward component, which would theoretically increase to 460 meters per second, if the travel to the Equator should be carried through. Likewise the antitrade would reach enormous eastward components on its travel from Equator to the pole.

The system of trades and antitrades may therefore only be established in low latitudes, where the effect of the earth's rotation is still moderate. In the Temperate Zone a more complex system of motion is established. The trade wind from the pole divides into different branches polar currents between which channels remain open to corresponding branches of the antitrade-tropical currents. Thus the antitrade of the Temperate Zone appears not only as an upper poleward current but also as tropical currents on the ground.

The particular polar currents will, when starting as northerly currents, tend to deviate into NE. or even ENE. currents; likewise the tropical currents deviate from southerly to SW. or WSW. currents. We thus have a system of alternate polar and tropical currents beside each other, winding up spirally round the earth's axis.

These currents will hinder each other from obtaining the great west-east or east-west components which were to be expected from the effect of the earth's rotation.

At the limit between a polar current and a tropical current to the east of it, the two currents are deflected from each other, so that an air deficit results above the region of their mutual limit. The low-pressure system, formed in that way, corresponds to a cyclone family. *The cyclone family is thus a boundary phenomenon between the left flank of a polar current and the adjacent tropical current.* The single cyclones of the family transform the boundary between the two currents—the polar front—into a complicated wavy curve which constantly changes its form. Moreover, the polar current will contain within itself all the eddies of vanishing cyclones, so that each polar air particle of necessity performs complicated motions before it reaches the Tropics.

The formation of cyclones as boundary phenomena between a polar and a tropical current is one of the natural brakes against the enormous east-west and west-east components, which should otherwise result in both currents. As soon as an easterly polar current and a westerly tropical current become too strong, a cyclone forms between them and makes the currents encroach upon each other, diminishing their differences of velocity. A polar air particle traveling from pole to Tropics, successively comes under the influence of the different cyclones of the family. Each cyclone deviates the motion of the particle from easterly to northerly or even westerly, so that it again may advance some distance toward the Tropics without obtaining too great a westward velocity component.

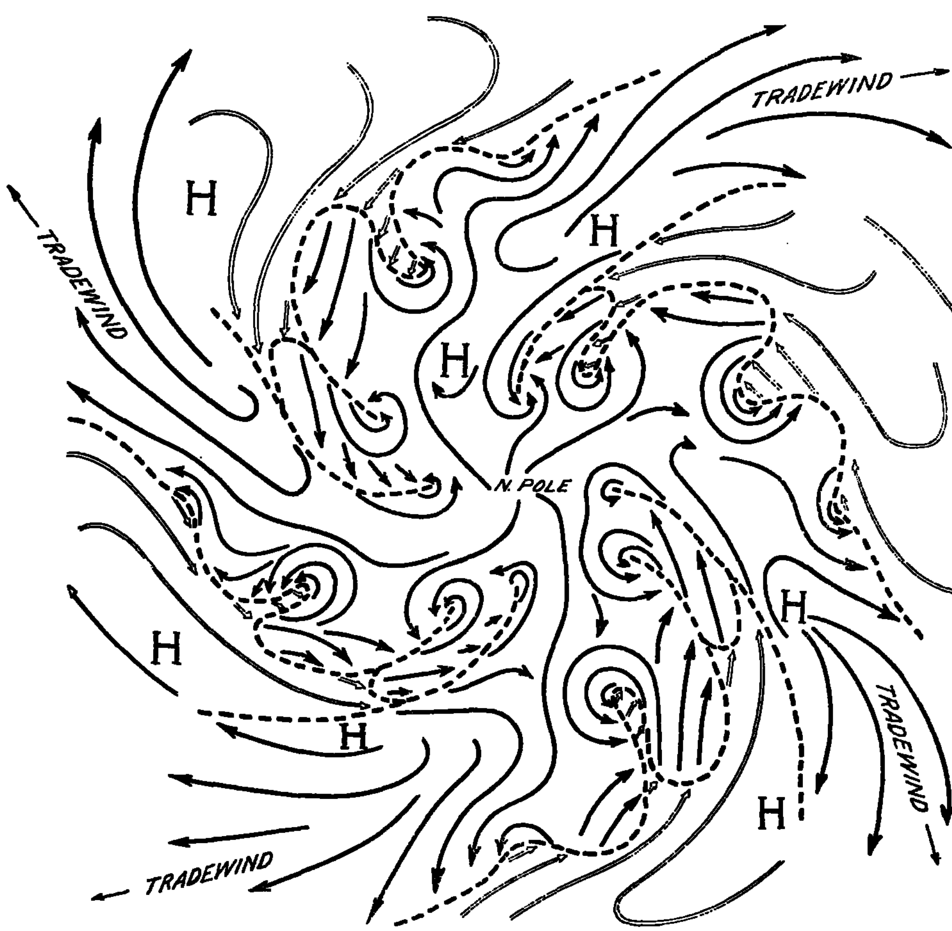

FIG. 6.—[Original fig. 12.] General extratropical circulation of the atmosphere.

A second brake against the great west-east and east-west component acts where a polar current borders a tropical current to the east of it. The two currents, owing to the earth's rotation, will there press together so that they hinder each other from obtaining the velocities to be expected as an effect of the earth's rotation alone. The result of this pressing together appears in an accumulation of air-masses above the region of the mutual limit of the two currents, or in the field of pressure as the formation of a HIGH. This process represents the general formation of moving anticyclones: *A moving anticyclone forms as a boundary phenomenon between the right flank of a polar current and the tropical to the west of it.*

The moving anticyclone is thus formed between two successive cyclone families and follows their motion from west to east round the

[10] Cf. *Geofysiske Publikationer* Vol. II, No. 4, pp. 84–88.

pole, consequently the anticyclone moves with the same speed as the cyclone families, but more slowly than the particular cyclones which during their existence move from the rear to the front of their family.

PERIODS OF METEOROLOGICAL ELEMENTS DUE TO CYCLONE FAMILIES AND MOVING ANTICYCLONES.

Disregarding the obstructions caused by the large continents, cyclone families and moving anticyclones may be imagined to travel continually around the pole.

This movement will produce a periodicity in the meteorological elements throughout the Temperate Zone. Places far north will, for instance, only receive precipitation from the first passing members and places far south only from the last passing members of a cyclone family. Places situated centrally in the cyclone belt, so that they receive precipitation from all the cyclones passing, will have a short spell of fair weather during the passage of the anticyclone which separates successive cyclone families. If the cyclone families perform perfect circuits around the pole,[11] the length of the periods should be equal in all parts of the cyclone belt. They may, however, be of different length in the two hemispheres, as the cyclone families north and south of the Tropics form two independent systems.

A count of the cyclone families passing over Europe in 1921 gives 66 as the total number. This would give a mean duration of 5.5 days, but the authors recognize an error of about 10 per cent.

Various investigators have found short period fluctuations in the climatic elements; probably the most thorough was that of Defant,[12] who found for a single year, 1909, a period of about 5.7 days in the Northern and 7.2 days in the Southern Hemisphere. The cyclone family period of 1921, 5.5 days, agrees so well with the precipitation period from 1909 Northern Hemisphere of 5.7 days that the two periods are considered as identical within the limits of errors.

DISCUSSION.

ALFRED J. HENRY.

The central idea in the foregoing is that cyclones are formed along lines of discontinuity which separate masses of dense polar air from lighter air of tropical origin. The underlying assumption is that the dense polar air is moving westward immediately adjacent to a current of warm air moving eastward. When for any reason the warm current bulges to the northward intruding into the westward moving polar air, the greater density of the latter will cause it to flow along the ground and to cause the warm air to ascend, thereby producing cloud and rain. The condensation of water vapor and the latent heat thus evolved will augment the ascensional movement thus mechanically originated which, together with the modification of the original motion of the air due to the earth's rotation, will create a cyclone. This, in brief, is the reviewer's understanding of the mode of origin of cyclones as advanced by the authors. The various changes which the cyclone undergoes in its brief course has been outlined in the pages preceding.

In view of the fact that the phenomena of cyclones and anticyclones are at best very imperfectly represented on weather maps by surface conditions it must be assumed that the specifications hereinbefore presented should be considered as applying to the conventional cyclone and anticyclone, or possibly to the average of conventional cyclones and anticyclones as they enter Norway.

Forecasters in the United States will be quick to recognize in the specifications hitherto mentioned many familiar phenomena in connection with the movement of cyclones and anticyclones. There are, however, some points of difference between the experience of the Norwegian forecasters and those of the United States; some of these have been mentioned in the series of footnotes appended to this article; others are not easily disposed of within the limits of a footnote. In what follows I shall refer to the most obvious differences between the larger features of the Bjerknes scheme as contrasted with the experience of forecasters in the United States.

Latitudinal differences.—Undoubtedly the origin and development of cyclones and anticyclones are more clearly defined in the latitude of Norway (north 58° to 77°) than in the United States. For the most part cyclones and anticyclones which traverse the latter arrive on its frontiers as fully developed systems of wind circulation. Secondary cyclones, however, frequently develop over the southern and middle portions of the Plateau region in barometric troughs which pass across those regions (from west to east). The development of a primary cyclone, using that term as synonymous with the A-cyclone of the Bjerknes terminology, in the United States is a very rare occurrence.

Cyclone families—The ability to foresee the occurrence of cyclones in families as contemplated in the Bjerknes scheme would be of very great significance in extending the forecasts beyond the conventional period. For reasons indicated in the preceding paragraph it is not only difficult to identify the *A* cyclone of each family on the charts of the United States Weather Bureau, but also, it seems highly improbable from the past experience of forecasters in this country that the occurrence of cyclones in families takes place in the latitudes of the United States with sufficient regularity to make the precept of definite value in long-range forecasting;[13] moreover cyclones at times move southeastward from the Pacific to the Gulf of Mexico and thence northeastward to the St. Lawrence Valley, or develop over the Gulf of Mexico and move similarly, apparently without regard to the development and movement of cyclones along the northern circuit. These cyclones sometimes occur in groups and apparently have no relation to those of the northern groups.

Precipitation.—The area of precipitation in the advance of cyclones in the United States is rarely symmetrically distributed around the front of the cyclone, but is irregularly distributed according to geographic position of the cyclone and the season.

On the Pacific coast and in the Plateau and Rocky Mountain region precipitation occurs as a rule in the rear of the cyclone center instead of the front. On the immediate coast the winds of winter, as is well known are relatively warm as compared with those of the land, and the precipitation that is associated with the movement of the cyclone is of the orographic rather than the cyclonic type. In the Bjerknes type of cyclone the cold air to the eastward of the cyclone is made to curve around the north side of the cyclone and swing in toward the center as a northwest wind. While this movement probably takes place in the conventional cyclone after

[11] The evidence of the Signal Service international series of observations seems to point to a gap in the path of cyclones around the pole as for example over northern Siberia.

[12] A. Defant: Die Veränderungen der allgemeinen Zirkulation der Atmosphäre in den gemässigten Breiten der Erde. *Wiener Sitzber*, 1912, p. 379.

[13] See footnote No. 8 on p. 470.